Predictive simulation of tokamak discharge behaviour based on simple scalings

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Introduction

The operation of tokamak experiments can be facilitated by control room tools that predict the plasma discharge behaviour based solely on machine parameters and requested waveforms of coil currents, gas puff, etc. We describe here a publicly available simulation toolkit fully based on open source software that implements a variety of models which are based on simple physics relations. These are obtained from empirical scalings of the plasma density, the confinement time etc. and allow to predict basic properties of a tokamak discharge like actual plasma density, stored energy, ohmic transformer flux consumtion and transition times to and from high-confinement mode (H-mode). The data described is from the ASDEX Upgrade tokamak, however the tools can be ported relatively easily to other machines.

Experimental data base

In the context of the present model, tokamak transport physics is described in terms of scalar quantities. For ASDEX Upgrade, four data sets are used to determine parameter dependencies: 803 stationary ELMy H-mode phases selected for largest variation of engineering parameters B_t, I_p, P_{heat}, gas puff and plasma shaping (triangularity). 416 phases from the ASDEX Upgrade contribution to the international confinement database, 916 phases (H-mode) and 386 phases (L-mode) have been compiled to map out operational regime boundaries.

The central line-averaged plasma density $\overline{n}_e$ can be feedback-controlled, or result from a prescribed gas fuelling rate in the divertor or in the main chamber ($\Gamma_{0,div}$, $\Gamma_{0,main}$, both in atoms/second). Alternatively, the neutral gas density in the divertor $n_{0,div}$ or main chamber $n_{0.main}$ can be feedback controlled. It is assumed that in steady state the controlled quantities are actually obtained. The plasma density $\overline{n}_e$ is approximated by a power law $\overline{n}_e = A\ \Pi_i\ Q_i^{\alpha_i}$ with the prefactor A and exponents α_i obtained by log-linear regression (table 1).

The plasma shape dependence of the density scaling is expressed through the upper triangularity δ_u. The lower triangularity is strongly correlated with β_p and therefore less suitable. In the currently implemented models, the Grad-Shafranov equation is not solved. Instead, δ_u is obtained by linear regression of shaping coil currents and I_p (Fig. 1, rms error 17.9%).

The energy confinement time ($\tau_{tot} = W_{\mathrm{tot}}/P_{\mathrm{heat}}$), L-H and H-L transition power thresholds ($P_{\mathrm{L}\rightarrow\mathrm{H}}$, $P_{\mathrm{H}\rightarrow\mathrm{L}}$) and minimum ("natural") H-mode density are determined by scalings with engineering parameters and $\overline{n}_e$. Finally, the core radiated power P_{rad} and plasma resistance R depend on plasma temperature which is approximated by a dependence on W_{tot} and $\overline{n}_e$. A list of scaling coefficients is given in table 2.

Implementation

The temporal discharge behaviour is described by sets of coupled ordinary differential equations. They are integrated in time using the Scicos simultion toolkit (`www.scicos.org`), distributed as part of the Scilab mathematical package (`www.scilab.org`). Several models with

Table 1: Scalings of $\overline{n}_e$ as a function of $n_{0,main}$, $n_{0,div}$, $\Gamma_{0,main}$, $\Gamma_{0,div}$ for H-mode and L-mode

prefactor	I_p	B_t	$P_{\rm tot}$	$0.1+\delta_u$	$n_{0,main}$	$n_{0,div}$	rmse
$10^{19}m^{-3}$	MA	T	MW		$10^{19}m^{-3}$		%
			H-mode				
14.60	1.04 ± 0.02	-0.45 ± 0.02	0	0.12 ± 0.01	0.11 ± 0.01		15.2
7.701	1.08 ± 0.05	-0.30 ± 0.04	-0.14 ± 0.02	0.11 ± 0.01		0.15 ± 0.01	13.2
					$\Gamma_{0,main}$	$\Gamma_{0,div}$	
					$10^{21}m^{-3}s^{-1}$		
11.68	1.07 ± 0.05	-0.42 ± 0.05	0	0.08 ± 0.01	0.08 ± 0.01		14.2
9.403	1.00 ± 0.11	-0.60 ± 0.09	0.20 ± 0.04	0.04 ± 0.01		0.05 ± 0.01	11.1
			L-mode				
					$n_{0,main}$	$n_{0,div}$	
14.84	0.64 ± 0.07	-0.41 ± 0.06	0.11 ± 0.02	0.30 ± 0.03	0.16 ± 0.01		17.4
4.833	1.78 ± 0.21	0.82 ± 0.09	0.10 ± 0.03	0		0.10 ± 0.03	9.4
					$\Gamma_{0,main}$	$\Gamma_{0,div}$	
9.608	0.13 ± 0.12	-0.21 ± 0.14	0.09 ± 0.04	0.17 ± 0.06	0.24 ± 0.03		17.9
8.780	0	0.49 ± 0.24	-0.13 ± 0.08	0.56 ± 0.12		-0.07 ± 0.05	7.2

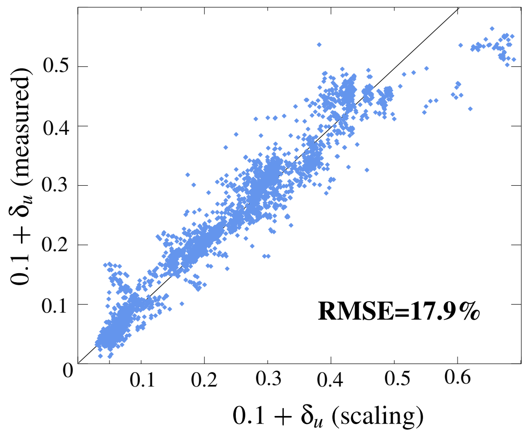

Figure 1: *Scaling of the upper triangularity*

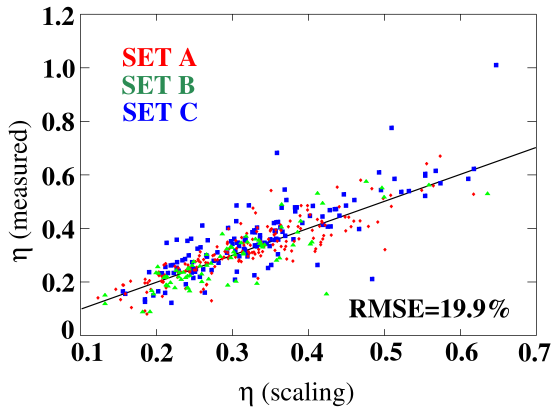

Figure 2: *Scaling of the plasma resistivity*

different complexity are available. Models are easily built by adding building blocks and logical connections to a diagram edited by a graphical user interface. Each simulation run is preceded by a data collection phase (machine dependent but model independent) and succeeded by a post-processing step to perform various consistency checks and issue warnings to the operator. The entire suite is controlled by an embracing Bourne shell script, which is called once per discharge and takes a few seconds to run. For waveform input and output, interface blocks to MDSplus (`www.mdsplus.org`) trees are implemented. The software described here is available for download at `www.ipp.mpg.de/~Wolfgang.Suttrop/mdsplus/tokfsim`.

Dynamical confinement model

Figure 3 shows the block diagram of a model for plasma density, stored energy, L-H/H-L transitions and ohmic flux consumtion. The scalings for (reciprocal) confinement time, plasma

Table 2: Scalings of energy confinement time τ_{tot}, L-H and H-L transition threshold powers $P_{\mathrm{L}\to\mathrm{H}}$, $P_{\mathrm{H}\to\mathrm{L}}$, core radiated power P_{rad} and plasma resistance R.

quantity	units	prefactor	I_p	B_t	P_{tot}	$\overline{n}_e$	$(0.1+\delta_u)$	W_{tot}	rmse
			MA	T	MW	$[10^{19}\ \mathrm{m}^{-3}]$		MJ	%
H-mode									
τ_{tot}	s	0.75	1.43 $\pm$0.03	-0.27 $\pm$0.03	-0.62 $\pm$0.01	-0.23 $\pm$0.02	0.12 $\pm$0.01		14.6
$P_{\mathrm{H}\to\mathrm{L}}$	MW	0.28		0.56		0.79			
P_{rad}	MW	0.017			0.080 $\pm$0.05	1.38 $\pm$0.07		-0.06 $\pm$0.07	35.2
R	$\mu\Omega$	0.02				0.78 $\pm$0.04		-1.16 $\pm$0.04	19.9
L-mode									
τ_{tot}	s	0.16	0.69 $\pm$0.07	0.33 $\pm$0.05	-0.53 $\pm$0.02		0.20 $\pm$0.03		16.7
$P_{\mathrm{L}\to\mathrm{H}}$	MW	0.51		0.56		0.79			

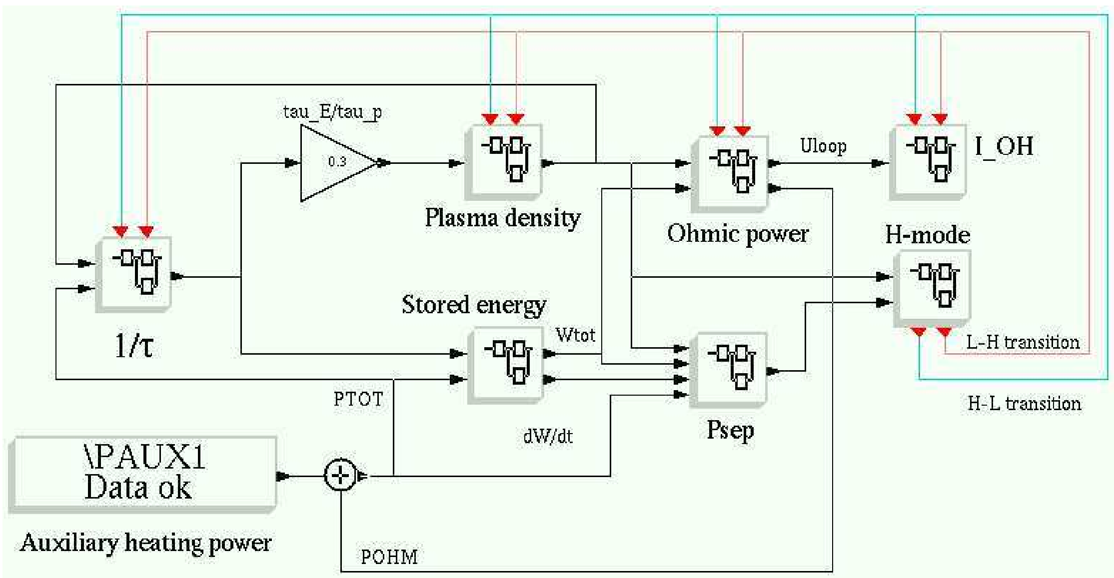

Figure 3: *Scicos model for L- and H-mode plasma density, stored energy and ohmic transformer flux consumtion.*

density, plasma resistivity, radiated power and H-mode threshold power are used in the blocks labelled "$1/\tau$", "plasma density", "Ohmic power", "P_{sep}" and "H-mode", respectively. These blocks are nested models and edited in separate Scicos sheets. This block hierarchy allows to maintain a clear structure in more complex models. The ohmic transformer current (block "I-OH") is integrated from the loop voltage using 3 fixed values of the plasma inductance at start-up, in L-mode and in H-mode and the scaling for plasma resistance. Variations of the poloidal field coil currents are taken into account by means of pre-calculated fixed values for their mutual inductances with the plasma column. The L-H and H-L transition is detected

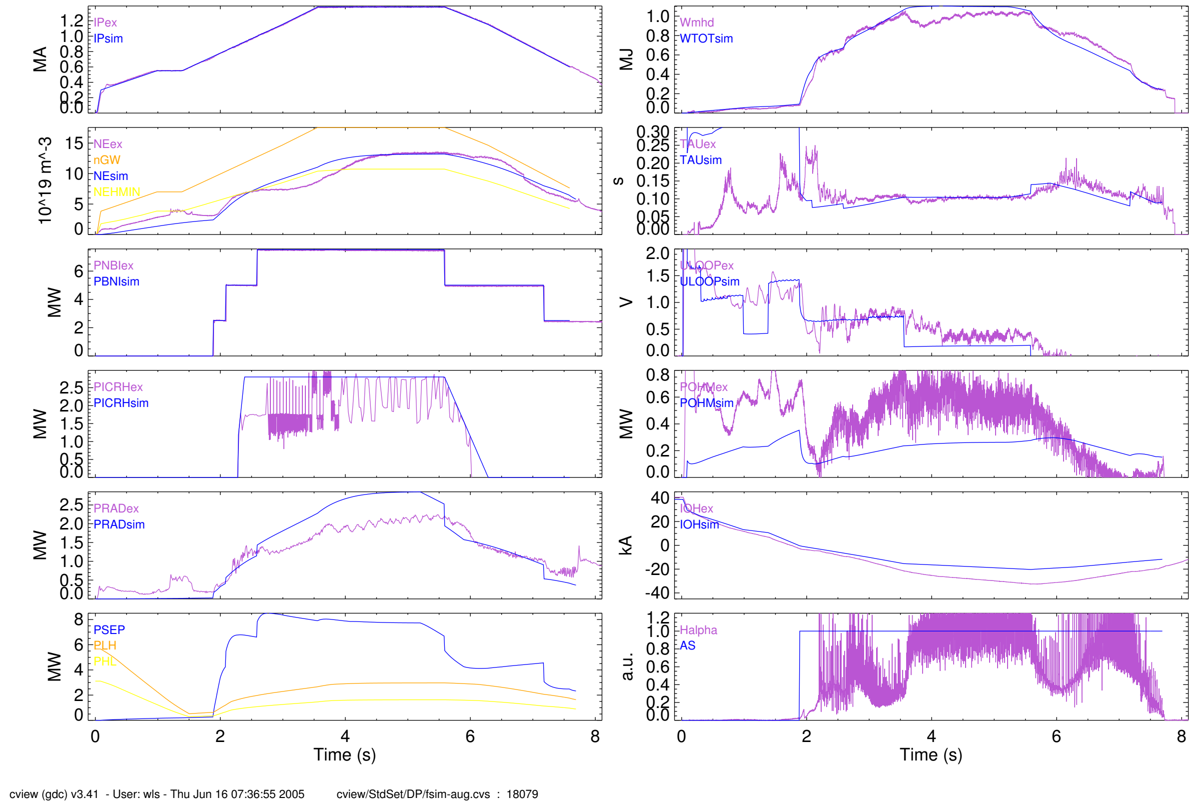

Figure 4: *Comparison of predicted and measured waveforms of ASDEX Upgrade shot 18079*

from comparing the separatrix power P_{sep} against P_{LH} and P_{HL}. Transition events are fed back to those blocks which use scalings that are regime dependent. One MDSplus input block is shown (“auxiliary input power”). All other input and output blocks in this model are hidden in nested complex blocks.

Results and discussion

Figure 4 compares predicted and measured waveforms of ASDEX Upgrade shot 18079. This pulse, at $I_p = 1.4$ MA, reaches H-mode quickly after the heating power ($P_{NBI} = 7.5$ MW and $P_{ICRH} \leq 3$ MW) is switched on. Feed-Forward gas puff is used during flat-top. The predicted density is reached, albeit with a larger time constant than predicted. The radiated power is somewhat overestimated. This is a result of variations of the impurity content which cannot be described by the simple scaling used. Nevertheless the stored energy and confinement time are reasonably accurately predicted. The loop voltage and ohmic transformer current are, in this example and generally, accurate to the level of $10 \ldots 20$ %, sufficient to estimate the maximum available pulse length and possible limitations from forces between the ohmic transformer and other poloidal field coils. A major limitation of the currently implemented models is the lack of a model for particle transport for ELMs. H-mode phases near the threshold with very low ELM frequency can result in strong density and radiation increase which alters the discharge behaviour considerably.